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Urban heat island research in Phoenix, Arizona

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URBAN HEAT ISLAND RESEARCH IN PHOENIX, ARIZONA

Theoretical Contributions and Policy Applications

BY WINSTON T. L. CHOW, DEAN BRENNAN, AND ANTHONY J. BRAZEL

The prodigious volume of applied and interdisciplinary heat island research in Phoenix, Arizona, was motivated by several factors intrinsic to the city and has contributed to formation of municipal policies geared toward sustainable urban climates.

The desert city of Phoenix, Arizona, is the focal point of the expansive Phoenix Metropolitan Area (PMA) (~37,000 km²) (Fig. 1). Since 1950, the PMA has experienced extensive land use and land cover (LULC) alterations, changing from a predominantly agricultural region to a metropolis mostly comprising residential suburbs (Fig. 2). Consequently, several interrelated environmental concerns arose that potentially threaten its long-term sustainability, including water scarcity (e.g. Wentz and Gober 2007), reduction of native biodiversity (e.g., Grimm and Redman 2004), poor urban air quality (e.g., Doran et al. 2003; Lee et al. 2007), and the urban heat island (UHI).

The last feature is the phenomenon of warmer urban areas vis-à-vis pre-urban or "rural" surroundings. Since it was first observed in London by Luke Howard (Howard 1833), the UHI has been thoroughly investigated in cities of varying size and climate type. It is caused by several factors directly attributed to LULC change, such as alterations to the surface energy balance from increased absorption of radiation energy, higher

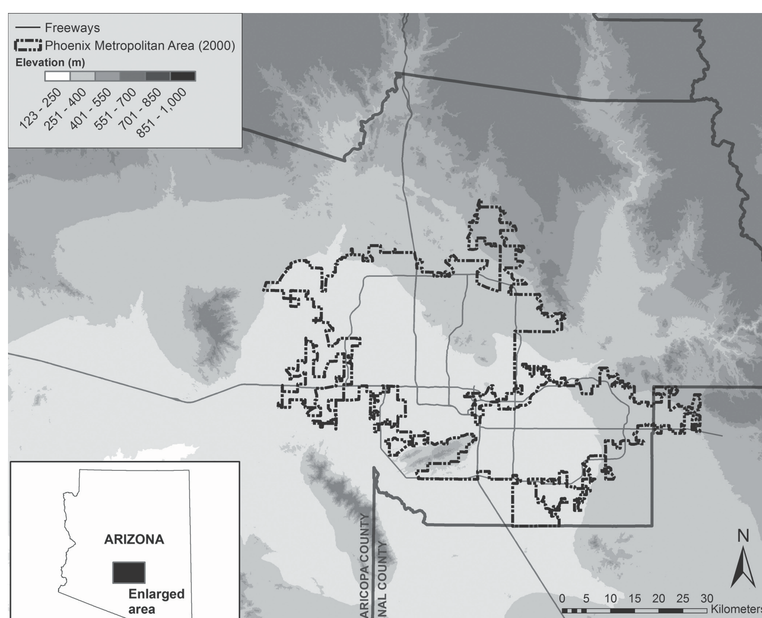

FIG. 1. The boundaries of the Phoenix metropolitan area (PMA) in 2000 and surrounding topography. Note the complex topography arising from mountains along the northern and eastern margins of the city.

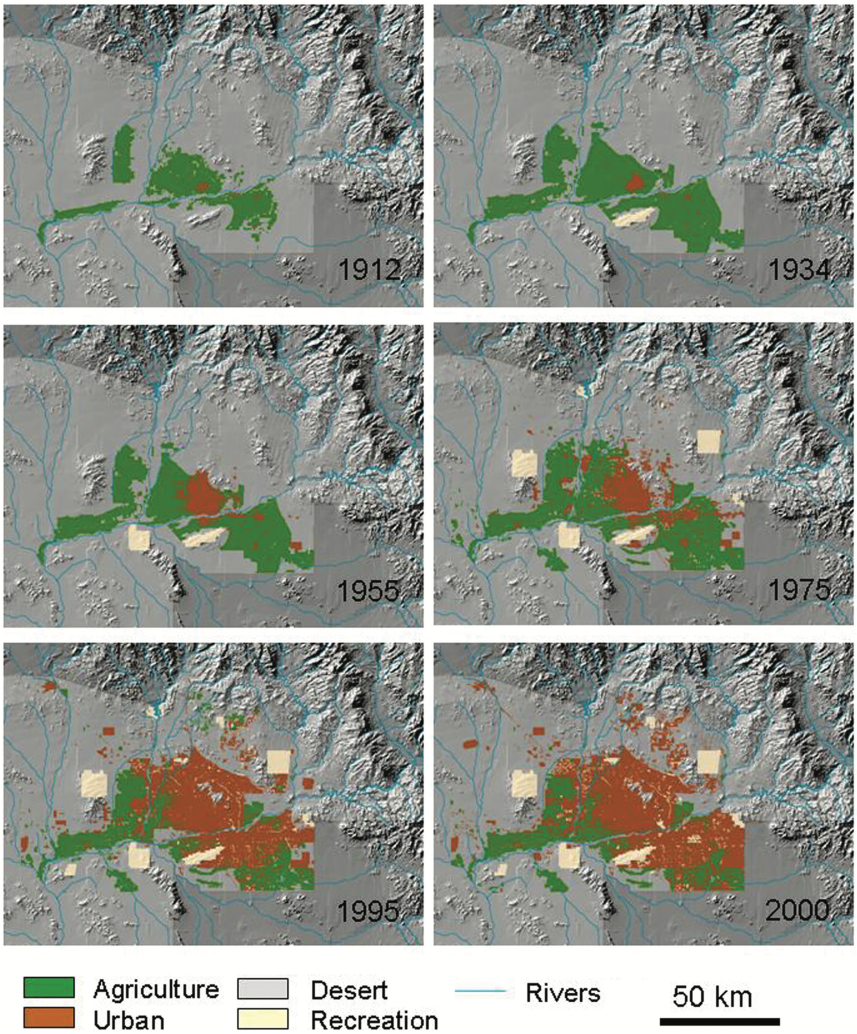

Fig. 2. Land use/land cover (LULC) change in the PMA from 1912 to 2000 illustrating the increase of urbanized land cover at the expense of desert and agricultural land use [Source: Central Arizona–Phoenix Long-Term Ecological Research (CAP-LTER)].

anthropogenic heat emissions, and decreased surface evapotranspiration in urban areas (Oke 1982). Magnitudes of maximum UHI intensity, defined as the largest difference between urban and rural temperatures (ΔT_{u-r}), are influenced by synoptic weather type, urban morphology, timing of temperature observations, and categorization of "rural" areas adjacent to the city (Chow and Roth 2006; Stewart 2011). Globally, Parker (2004, 2006) demonstrated that urbanization is an insignificant contributor to recent increases in global surface temperature relative to other factors. When coupled with these increases, however, local warming from the UHI intensifies the climate discomfort of urban residents and increases their vulnerability to heat stress (e.g., Wilbanks et al. 2007).

A large body of academic work exists on the Phoenix UHI relative to other cities. As of mid-2011, 55 studies directly examining urban–rural temperature differences have been published in the peer-reviewed literature. In contrast, a simple literature search done in June 2011 using the ISI Web of Knowledge (http://apps.isiknowledge.com) with the term "heat island <insert city>" for New York City, Houston, and Los Angeles resulted in 28, 34, and 10 studies, respectively. Research of urban temperatures in Phoenix also has a long history. Gordon (1921) in *Monthly Weather Review* surveyed temperatures throughout the Salt River Valley and mapped winter minimum temperatures with notable elevated isotherms over the nascent city of Phoenix (Fig. 3). The uncommonly broad extent of literature raises several questions of interest for urban meteorologists and climatologists: What factors motivated the development of UHI study in Phoenix? Are there generalized

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and discernable research themes and approaches? What findings or theoretical contributions have there been with respect to other cities in similar (or dissimilar) climates? Has communication of these research results directed public policy in the PMA with respect to UHI mitigation?

Therefore, this article comprehensively reviews UHI research occurring within the PMA and frames it in the context of a potentially useful case study of applied climatology within a major American city. We based our review on the body of available peer-reviewed journal articles, book chapters, technical reports, and governmental reports that study UHI phenomena within the city's geographical boundaries. We first examine a variety of factors that motivated UHI research within the city and then summarize research themes, approaches, and theoretical contributions arising from its study. Several examples of municipal policy arising from local research are analyzed, and this review concludes with some suggested recommendations for future investigation.

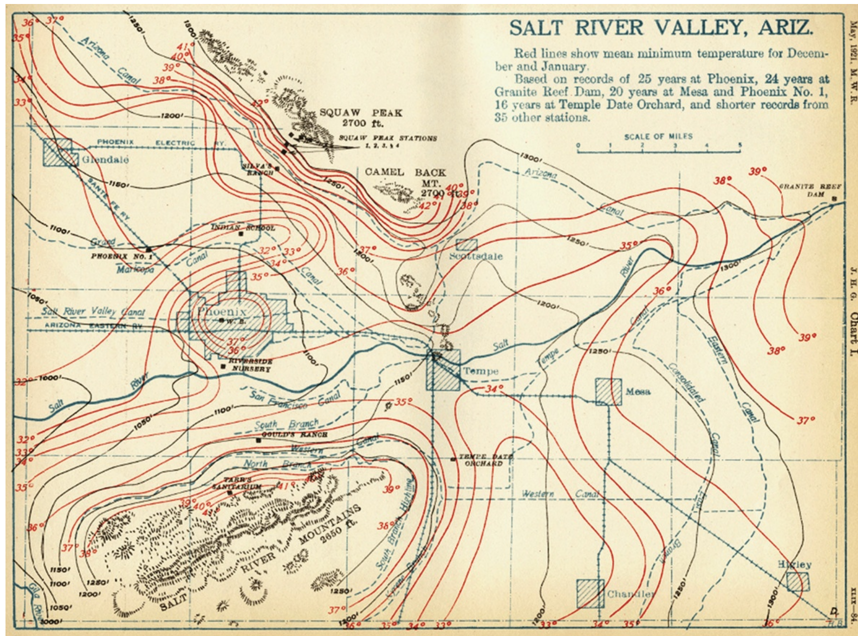

Fig. 3. Mean winter (Dec and Jan) minimum temperatures (°F) during the early twentieth century for the Salt River Valley, which includes a notable elevated isotherm pattern over the City of Phoenix (Source: Gordon 1921).

MOTIVATION FOR UHI RESEARCH. We propose that UHI research in the PMA developed from several extrinsic (i.e., originating outside of the PMA) and intrinsic factors. Theory derived from studies in other cities was a major extrinsic factor in formulating specific deductive research questions for Phoenix UHI research. Other factors included 1) the rapid post-1945 LULC change and its associated environmental changes; 2) projected impacts of a warmer, drier American Southwest from global and regional climate change; and 3) the prevalence of clear and calm synoptic weather conditions, especially during summer, that favor development of large UHI intensities throughout the year. To some degree, however, each of these factors could also apply to research occurring in other cities. We thus focus on three other important and unique intrinsic influences.

Partnerships between the academy and private sector agencies. A confluence of complementary interests existed between several local and national agencies keen on applied urban meteorological investigation within the PMA. These agencies included meteorology and climatology departments in Arizona's major research universities, the State Climate Office, the National Weather Service (NWS), the National Severe Storms Laboratory (NSSL), the Arizona Department of Environmental Quality (ADEQ), a private-sector energy and water company—Salt River Project (SRP)—and municipal governments at city, county, and state levels.

Several initiatives that developed from these partnerships were essential in expanding the scope of urban meteorology, and subsequent UHI research, within Phoenix. In 1977, the NWS, the National Climatic Center, and the Arizona Board of Regents formally partnered to supply and archive climate data from every meteorological station within the state. This partnership's intention was to publish monthly state climate summaries for interested users, which is an arrangement that continues to the present day. Throughout the 1980s, another partnership between SRP, Arizona State University, and the State Climate Office spurred and supported academic research into several urban climate topics, including the UHI. One major research objective of this union was to improving short-term weather forecasting models applied to urban areas. Another partnership in 1989 between the NSSL and the State Climate office resulted in the Arizona Thunderstorm Chase (AZTC) project, a real-time storm monitoring program operated by local university students and volunteers that gathered and transmitted urban thunderstorm data to NWS Phoenix (Cerveny et al. 1992).

Other partnerships within academic institutes, especially between science and social science disciplines, were also essential in guiding several research projects. An important organization that helped facilitate such research was the Central Arizona–Phoenix Long-Term Ecological Research (CAP-LTER) project, a National Science Foundation (NSF) program that investigates the complexities of human–ecological processes within the PMA. CAP-LTER has successfully fostered an academic environment that aids interdisciplinary communication and effectively eases the cross-pollination of ideas and methods between scientists and social scientists involved in UHI-related study. This was an important development in UHI research, as networking and exchange of ideas across disciplines were stressed by Mills (2006) and Oke (2006) as being critical for the development and progression of the study of urban meteorology and climatology.

A well-developed and extensive urban meteorological station network. Part of the *raison d'être* for the development of several aforementioned interagency partnerships was the high demand for climate data within the PMA. For instance, an increasing volume of data requests originated from the private sector in the early 1990s (e.g., SRP being keen on examining variations of urban insolation and temperature data for potential solar energy applications). Other stakeholders were interested in real-time, hourly climate data for agricultural or horticultural purposes in cities within the state (e.g., the University of Arizona) or for air pollution and flood hazard warnings in the PMA (e.g., Maricopa County government). Other municipal governments also required high-resolution urban climate data for policy issues such as air and water quality regulations, construction project designs, and energy and groundwater use (Brazel 1999).

These data requests would usually fall under the purview of the NWS; however, the urban-specific data could not be easily supplied as 1) most existing cooperative weather stations were limited in spatial extent and 2) these stations primarily recorded basic temperature and precipitation data lacking fine temporal resolution. The large interest for urban climate data precipitated the development of an extensive meteorological station network scattered throughout the PMA over a variety of LULC types (Fig. 4). These networks of real-time, automated weather stations were developed, and are currently operated, by a variety of stakeholders including the Maricopa County government and SRP. As of the end of 2010, there were 70 operational stations with professionally quality-controlled data available for interested researchers, either through downloads from online servers or by contacting the relevant agency (Table 1). Several station networks have been in operation since 1990, and this duration of high-quality data also facilitates historical research that would be problematic in other cities lacking a long-lived urban meteorological station network.

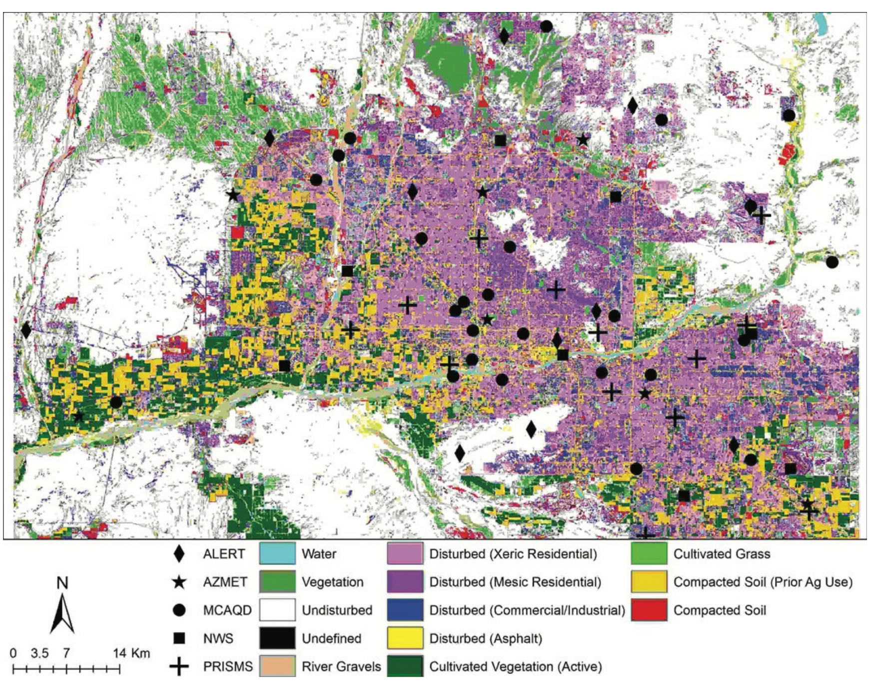

Fig. 4. 2005 LULC classification of the PMA (Buyantuyev 2005) with locations of operational urban meteorological stations. ALERT = Automated Local Evaluation in Real Time; AZMET = Arizona Meteorological Network; MCAQD = Maricopa County Air Quality Department; NWS = National Weather Service Automated Surface Observing Systems; PRISMS = Phoenix Real-time Instrumentation for Surface Meteorological Studies.

Table 1. Listing of operational urban meteorological station networks based within the PMA in 2010.

Station network	Operated by	Original network objective	Number of PMA stations in 2010
PRISMS (Phoenix Real-time Instrumentation for Surface Meteorological Studies)	Salt River Project (SRP)	Energy demand and solar research	16
AZMET (Arizona Meteorological Network)	University of Arizona	Agricultural and horticultural data	8
AQD (Air Quality Department)	Maricopa County	Urban air pollution	22
FCD (Flood Control District) ALERT (Automated Local Evaluation in Real Time)	Maricopa County	Urban flood hazard control	16
ASOS (Automated Surface Observing Systems)	National Weather Service (NWS)	Surface weather observation	8
TOTAL			70

Strong media coverage on UHI-related issues in the PMA. There has been persistent and robust coverage on the UHI that parallels the notable academic and private sector interest. We conducted an archival search of the newspaper of record in the state [*The Arizona Republic*; archives (and all cited articles) are available online at http://pqasb.pqarchiver.com/azcentral/advancedsearch.html] and noted 187 articles related to "urban heat island" published from January 1999 to December 2010. Local UHI coverage was extensive in both form and content, with articles such as 1) brief, factual reports of UHI impacts (e.g., "2010 Phoenix summer one of hottest ever due to overnight lows," 6 September 2010); 2) longer editorial columns (e.g., "Let's cool it! We got ourselves onto this heat island, we can get ourselves off it," 14 September 2003); 3) guest opinion columns from academic researchers (e.g., "Urban heat island affects Phoenix all yearround," 22 September 2007); and 4) in-depth, multi-page coverage of UHI research (e.g., "Cities are key culprits in weather shifts," 11 January 2009).

Television meteorologists from several PMA television network channels also regularly highlight the UHI, both in on-air broadcasts (e.g., www.myfoxphoenix.com/dpp/weather/heat-island-effect-7-9-2010) and by having informative and regularly updated UHI-related content online (e.g., KNXV-TV's heat center, available online at www.abc15.com/subindex/weather/heat_center). The interested public is thus easily able to watch archived footage of these broadcasts or seek basic, accurate information about the UHI and its impacts through the Internet. The broad extent of journalistic coverage of UHI in both established print and broadcast media appears to be rare when compared to other cities, and we argue that it possibly reflects—and cultivates—a strong level of public interest by local residents in knowing about and understanding the UHI.

SUMMARY OF UHI RESEARCH IN PHOENIX AND ITS THEORETICAL CONTRIBUTIONS. We reviewed, and subsequently summarized, a comprehensive list of published peer-reviewed UHI studies that examined the PMA UHI, which included research into surface and near-surface (~2 mAGL) ΔT_{u-r} (Table 2). Each study was categorized into distinct themes, each possessing implicit approaches that investigated relevant thematic topics. Notable results from papers categorized in each theme/approach, as well as their key contributions to UHI theory, have also been condensed. When examined according to UHI type, a large majority of studies examined near-surface temperatures within the urban canopy layer (Oke 1976). Across all themes, far fewer studies on either the surface or boundary-layer UHI exist, and there was no published research on subsurface UHI. This skewed distribution is unsurprising, primarily because fieldwork campaigns with direct canopy-layer temperature observations are relatively easier to undertake compared to other UHI types (e.g., remotely sensed based surface UHI observations can be limited by gaps in spatiotemporal data coverage).

UHI research themes within the PMA. The largest number of papers reviewed dealt with the physical study of UHI over different spatiotemporal scales. In general, study methodologies analyzed 1) meteorological station and/or vehicle traverse data, 2) remote sensed data from airborne or satellite platforms, and 3) data derived from scale, statistical, or numerical modeling techniques. Results from most studies complemented findings from elsewhere (see, e.g., Arnfield 2003;

Table 2. Summary of themes, approaches, and notable results and theoretical contributions taken from published UHI studies within the PMA.

Theme	Approach	Notable results and theoretical contributions (associated papers; *surface UHI papers are italicized*)
Physical study	Description and spatial mapping of UHI	Rapid growth of UHI extent in conjunction with urbanization (Gordon 1921; Hsu 1984; Brazel et al. 2007)
		Distinct "oasis" effect of lower daytime urban core temperatures relative to desert (Balling and Brazel 1987; Brazel et al. 2000; Georgescu et al. 2011)
		Assessment of geostatistical accuracy of interpolated "soft" data (Lee et al. 2008)
	LULC change and time series analysis	Significant increase in mean urban minimum temperatures over long time scales, but no long-term change in urban maximum temperatures (Cayan and Douglas 1984; Hansen et al. 1999; Lee and Ho 2010; Svoma and Brazel 2010)
		Canopy-layer UHI intensities greatest at night, and under clear and calm conditions (Brazel and Johnson 1980; Fast et al. 2005; Stabler et al. 2005; Hedquist and Brazel 2006; Sun et al. 2009)
		Surface and canopy-layer UHI intensities strongly related to LULC type, with lowest temperatures over vegetated surfaces (Brazel and Johnson 1980; *Balling and Brazel 1988, 1989*; *Stoll and Brazel 1992*; Stabler et al. 2005; *Hartz et al. 2006b;* Chow and Svoma 2011)
		Larger $\Delta T_{u\text{-}r}$ magnitudes when "rural" LULC is agricultural/grass vs. desert (Hawkins et al. 2004)
	Wind and topoclimate impacts	Complex topography induces katabatic flows directly affecting diurnal UHI dynamics, possibly diminishing influence of thermally driven UHI circulations (Gordon 1921; Balling and Cerveny 1987; Brazel et al. 2005; Sun et al. 2009; Fernando 2010)
	Multiscale urban climate modeling	Strong influence of thermal admittance, building geometry and vegetation on microscale temperatures (Brazel and Crewe 2002; Chow et al. 2011)
		Reasonable accuracy of "urbanized" mesoscale climate modeled near-surface temperatures with observed data over different seasons (Grossman-Clarke et al. 2005, 2008; Georgescu et al. 2008, 2009a,b)
		Use of coupled UCM–Noah–Weather Research and Forecasting (WRF) model improves agreement between observed and modeled near-surface temperatures (Grossman-Clarke et al. 2010)
Biophysical impacts	Human discomfort and impacts on flora/fauna	Detrimental impacts on human comfort and on flora/fauna development (Baker et al. 2002; Hartz et al. 2006a)
		More residential heat-related dispatch calls in conjunction with larger UHI intensities (Golden et al. 2008)
	Spatial analysis of urban heat vulnerability	Urban heat vulnerability increased with larger UHI intensities, with significant socioeconomic variations over different spatiotemporal scales (Harlan et al. 2006; *Jenerette et al. 2007*; Ruddell et al. 2009; *Buyantuyev and Wu 2010*; *Jenerette et al. 2011*; Chow et al. 2012)
	Impacts on urban water and energy use	Increasing UHI intensity results in greater energy demand from increased air conditioning use within residential and commercial sectors (Golden 2004; Golden et al. 2006)
		Within transportation sector, significant increases in evaporative hydrocarbon emissions were linked to UHI (Otanicar et al. 2010)
		Residential water use and demand is positively correlated to UHI intensity (Balling and Gober 2007; Guhathakurta and Gober 2007, 2010)
Sustainable mitigation	"Green" landscaping	Vegetated ("green"), non-native landscaping in residential suburbs significantly lower urban temperatures, but sustainability has been questioned (Gober et al. 2010; Chow and Brazel 2012)
	Modifying thermophysical characteristics of materials	Increasing surface emissivity and albedo are potentially effective in reducing daytime and nighttime urban temperatures (Emmanuel and Fernando 2007; Gui et al. 2007; Silva et al. 2009, 2010)
		Shade canopies with photovoltaic cells reduce daytime urban temperatures and can also contribute to local sustainability (Golden et al. 2007)

Roth 2007). Two examples include the confirmation that ΔT_{u-r} occurs under clear and calm weather conditions and the strong correlation between LULC change from urbanization with UHI extent and intensity (Fig. 5). There were, however, several novel theoretical contributions. Researchers based in the PMA considered methodological implications of UHI data accuracy through assessing geospatial interpolations of soft data (Lee et al. 2008) and also by examining the influence of the "rural" definition when evaluating magnitudes of ΔT_{u-r} (Hawkins et al. 2004). Further, the PMA is sited within notably complex terrain, which greatly enables insights into topographic impacts on UHI intensity (e.g., through dynamic, large-scale katabatic flows; Brazel et al. 2005). Finally, the fine spatiotemporal quality of observational urban meteorological data also permits useful evaluations of climate model performance, especially when the focus is on testing urban parameterization schemes (Grossman-Clarke et al. 2010) or on how historical urban development alters surface energy budgets and thermodynamics (Georgescu et al. 2009a,b).

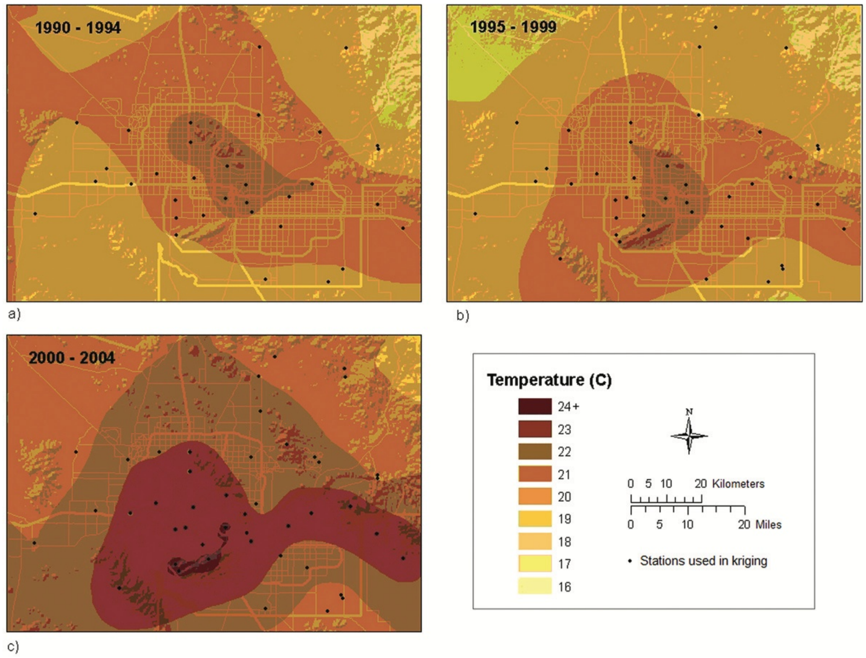

Fig. 5. Mean monthly (Jun) minimum air temperature patterns interpolated through ordinary kriging over 5-yr periods in the PMA: (a) 1990–94, (b) 1994–99, (c) 2000–04. Temperature data were taken from 37 stations distributed throughout the PMA (Source: Brazel et al. 2007). The increase in UHI spatial extent is especially evident when compared to Fig. 3.

The second theme encompasses research into the local biophysical impacts arising from the growing UHI. Studies associated with this theme largely occurred after the understanding of local UHI physical processes matured, with the first paper being published in 2002. Relevant approaches included on 1) how UHI directly impacts flora and fauna health; 2) how human vulnerability to heat is exacerbated by the UHI (i.e., the relationship between a population's physical exposure to increasing temperatures with its adaptive capacity to this hazard); and 3) how elevated urban temperatures influence energy and water use. An important methodological characteristic was that studies within this theme generally analyzed physical data in conjunction with quantitative socioeconomic data obtained from a variety of sources (e.g. academic surveys, municipal governments, or the U.S. Census). While there were several issues of data compatibility arising from this approach (e.g. spatiotemporal disconnect between census tract and station/traverse temperature data), the findings and conclusions from these studies are largely robust and are important contributions towards quantifying the detrimental physical and social impacts of UHI on PMA residents.

The previous research theme also influenced the concurrent, and complementary, study of sustainable UHI mitigation. Through largely prognostic numerical modeling methods, studies generally explored questions related to urban sustainability[1] (i.e., how would altering the urban environment benefit local residents with respect to the UHI?). Existing approaches developed elsewhere about UHI mitigation (e.g., engineering and landscaping changes through modification of albedo and building thermophysics, and from "greening" the urban

[1] A sustainable city can be defined as a settlement that is designed, built, and managed in ways that, over time, are able to improve human health, quality of life, and commerce without excessive consumption of natural resources (Martin 2008). This implies that municipal governments and residents attempt to prioritize environmental considerations equally with social and economic issues, and also aim for resource use efficiency for societal benefit (Mills 2006).

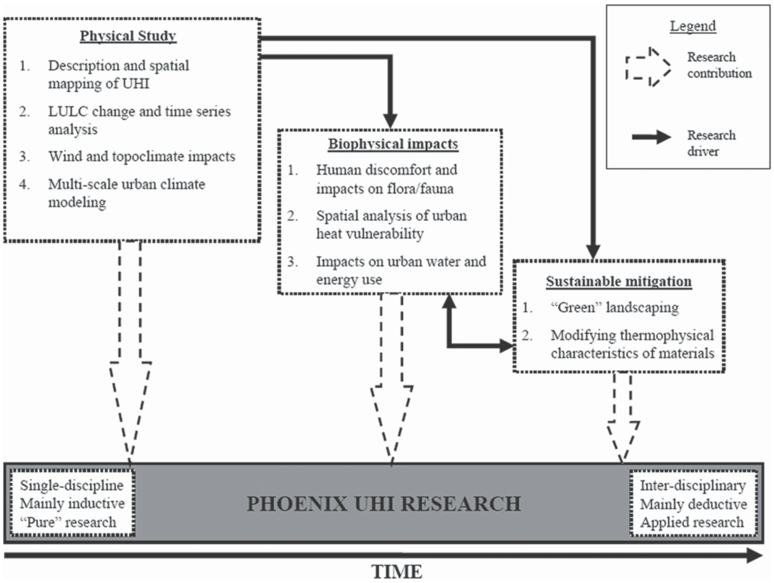

Fig. 6. The chronological development of major UHI research themes and approaches (within dashed rectangle boxes) with their contributions to knowledge development of the PMA UHI. Initially, conclusions arising from physical study of the UHI drove research into its 1) biophysical impacts and 2) sustainable mitigation, while study into both these latter themes often had complementary research drivers. The transition of single-discipline to interdisciplinary research is reflective of the maturity of UHI study in the city.

landscape) were tested and evaluated. An important contribution to sustainable urban climate knowledge involves assessing the local effectiveness of urban forestry in the PMA. As clearly documented in other North American cities (e.g. Rosenzweig et al. 2009), increasing urban vegetation significantly reduces microscale surface and canopy-layer temperatures. The utility of greater urban greenery in Phoenix, however, would potentially be offset by increased municipal water usage, which is a scarce resource in a desert environment. As per capita residential water use in Phoenix is significantly higher compared to other U.S. cities [856–1,514 liters (226–400 gallons) vs. the daily U.S. per-capita average of 379 liters (100 gallons); Yabiku et al. 2008], widespread urban forestry that is generally applicable elsewhere would likely increase this desert city's vulnerability to drought (Morehouse et al. 2002).

Finally, a complementary review of the chronological development of UHI research (from 1921 to 2012) revealed interesting epistemological developments, especially from "pure" to applied research approaches (Fig. 6). Initially, researchers defined, explained, and modeled UHI physical characteristics via inductive methodologies based on singular scientific disciplines. Subsequently, applied UHI research ensued that 1) evaluated its impacts on urban residents and 2) assessed sustainable mitigation methods. The research questions and objectives of these latter themes were also largely driven by results and conclusions from earlier research. As a consequence of initiatives stemming from CAP-LTER, these applied studies also generally utilized interdisciplinary methods arising from researchers with social science and engineering backgrounds. In due course, a greater volume of research gradually used deductive epistemologies formulated upon prior generalizations and theory, reflecting the maturity of UHI study in the PMA.

POLICY APPLICATIONS OF UHI RESEARCH. Given its broad themes and theoretical contributions, coupled with the varied motivations underpinning UHI research, it is unsurprising that ensuing municipal policies have been successfully applied towards addressing its detrimental impacts. In recent years, several city governments within the PMA actively utilized UHI research findings to implement policies to enhance urban sustainability. Specific policy aims largely involved techniques that 1) concurrently reduce UHI intensities, energy, and/or water consumption within local neighborhoods and 2) improve thermal comfort and air quality at street levels. These urban climate improvements were formalized and managed through design plans for future urban growth and development. In general, these plans proposed appropriate building forms, street design, urban forestry, shade structures, and development standards for sustainable residence in a desert city.

Two examples from the City of Phoenix are particularly illustrative. First, the Downtown Phoenix Urban Form Project (http://phoenix.gov/urbanformproject/) was a collaborative process including planners, scientists, and municipal officials that explicitly discussed thermal benefits arising from optimal building forms and massing standards, reflective paving and street materials, as well as supplementary shading structures at street level.[2]

[2] One of the authors (DB) was the principal planner for the City of Phoenix Planning Department and was tasked as the project manager for the submitted plan.

Ultimately, the project proposed future urban zoning policies and codes aimed at reducing heat discomfort within the city core (City of Phoenix 2008) (see sidebar). Second, the Tree and Shade Task Force developed a plan (SHADE Phoenix) providing a roadmap towards an average of 25% shade canopy coverage for the entire city by 2030 (http://phoenix.gov/PARKS/shade.html). Based on existing local research into the benefits of urban green spaces towards thermal comfort in Phoenix, the task force recommended the judicious use of urban forestry techniques (i.e., using drought-resistant flora and physical shade structures to mitigate UHI; City of Phoenix 2010). Recommendations from both plans were adopted by the Phoenix City Council within the same year that each plan was published.

Other initiatives and policies explicitly aimed at mitigating UHI also existed in extensively developed residential suburbs. Several municipal governments (e.g., the cities of Chandler, Glendale, Peoria, Scottsdale, and Tempe) actively promoted urban sustainability by encouraging homeowners with extensive mesic landscaping to convert to low-water demand xeric vegetation ("xeriscaping") (Fig. 7). For instance, as part of a larger sustainability initiative, the City of Mesa implemented a popular rebate policy in 2007 that offered $500 for homeowners to convert at least 46.5 m^2 (500 square feet) of existing mesic

THE DOWNTOWN PHOENIX URBAN FORM PROJECT

In 2006, the City of Phoenix initiated the Downtown Phoenix Urban Form Project. Its purpose was to examine current development patterns and to identify the "urban form" that development should take as the downtown core evolves over the next 20–30 years. A key component of the future urban form focused on how both modifying the existing environment and guiding the form of new development can be used to mitigate UHI. Reducing urban temperatures was critical to the long-term success of the project because the UHI strongly exacerbates the current undesirable pedestrian environment resulting from the natural hot arid environment.

A partner in the consultant team, Studio MA Architects, led the process of researching current UHI conditions in downtown and ultimately in preparing development standards. Previous research conducted by numerous Arizona State University (ASU) scientists was an invaluable resource in facilitating understanding of the UHI phenomenon in Phoenix. The existing theoretical knowledge greatly minimized the additional work necessary for the consultant to complete.

New, location-specific research at downtown was conducted by the partner, augmented by input from ASU researchers familiar with the UHI that were now working with the consultant team. The major activity undertaken was to conduct both canopy-layer and surface temperature measurements at critical points within downtown. The team was interested in microscale temperature variations arising from urban and natural materials located in direct sunshine versus shade, as well as on the influence of color on the material temperatures. The results of the partner's research not only addressed the preferred choice of urban materials but also aided understanding on related issues such as wind movement, building massing, street-level shading options (Fig. S1), and the cooling impacts of incorporating vegetation and water into the project designs. These studies also greatly contributed to a design strategy that improves pedestrian thermal comfort by incorporated several cooling elements (e.g. building wall, tree, and walkway shading; effective ventilation; and evaporative moisture misters), which potentially reduces outdoor standard effective temperatures by ~15°C (27°F) in summer.

This research culminated in the preparation of "Chapter 4: Sustainable Development in a Desert Climate" of the plan (City of Phoenix 2008). This chapter identified specific recommendations for addressing UHI mitigation and pedestrian comfort in the process of preparing a form-based code for downtown. A major benefit resulting was that, depending on the local urban form and LULC, the recommendations could also be applied to development throughout the Phoenix and the broader metropolitan area.

Fig. S1. Present-day streetscape (2nd Ave.) in downtown Phoenix, illustrating the influence of sustainable street-level shading. Previously, a single strip of palm trees provided little pedestrian shade. To increase thermal comfort and reduce daytime urban ambient temperatures, the Downtown Phoenix Plan recommended planting 1) a double row of broad canopy, low-water demand trees to increase shading and 2) low shrubs or screens to reduce pedestrian exposure to longwave radiation emitted from the adjacent asphalt road (Source: City of Phoenix 2008).

Fig. 7. Typical (a) mesic to (b) xeric residential landscaping in the PMA. The "xeriscaping" policy promoted by several PMA cities involves landscape conversion of water-intensive plants to low-water-demand, drought-resistant vegetation (Source: CAP-LTER).

landscaping to xeriscaped yards (City of Mesa 2010). These cities work in conjunction with the Arizona Department of Water Resources, which provides an informative database of drought-resistant plants for residential homeowners in the PMA (www.azwater.gov/azdwr/StatewidePlanning/Conservation2/Residential/Outdoor_Residential_Conservation.htm#resoutdoorlandscape). A common aim among these municipal programs is towards reducing residential water consumption, while simultaneously maintaining a comfortable microscale thermal environment for homeowners.

These UHI mitigation policies can complement other urban responses to detrimental impacts arising from anthropogenic global warming, considering that alterations to regional weather and climate properties from cities have long been viewed as an analog for global climate change impacts (Changnon 1992). While the influence of the UHI on increases in the recent global temperature record is relatively minor compared to greenhouse gases, increased urban metabolism (e.g., urban transportation and energy generation emissions) and urban drivers of LULC change (e.g., suburban residential construction and deforestation) are problematic net sources of greenhouse gas emissions. The important corollary is that cities can also generate solutions via effective management of urban resources that reduces CO_2 emissions (Mills 2007). Thus, policies promoting sustainable mitigation of UHI at local/city-wide scales could potentially be beneficial at larger spatial scales.

CONCLUSIONS. Our review illustrates that Phoenix is an interesting case study for applied UHI research, especially in terms of how interest in this meteorological phenomenon from different stakeholders helped precipitate its study. More importantly, research results greatly aided in effecting municipal policies aimed at improving urban sustainability at the local scale of both its downtown and residential neighborhoods. Despite the hitherto prodigious study of PMA UHI, we also note that further developments could be recommended, such as the following:

1) Greater emphasis on translating UHI research results as an educational resource to schools, which would increase its awareness among youths and teachers. There has been recent and welcome work on this, with CAP-LTER developing educational UHI resources for both middle school children and educators through outreach programs and a specific Internet presence (Elser et al. 2011).
2) Specific research into urban boundary-layer and subsurface UHI, both of which are scarce compared to other UHI types. Results would be important for the development of urban climate model parameterization and physics.
3) Continued monitoring and assessment of costs and benefits of post-UHI policy action in PMA cities. For instance, would the economic costs of implementing the downtown Phoenix plan be offset by the benefits in increased visitors and commercial revenue from a more comfortable urban environment over the short and long term? If substantial economic benefits are assessed, it would present a persuasive argument for governmental policy makers to be more cognizant of UHI impacts, as well as allocate more resources towards its mitigation.

In conclusion, a seminal article by Oke (2006) recognized that the scope of urban climatology was then well represented in terms of conceptualization, theorization, field observation, and statistical, scale, or numerical modeling, but model validation, urban design planning and application, impact assessment, and policy development were relatively lacking. Our review of the motivations behind PMA UHI research (which includes a large degree of successful interdisciplinary collaboration), as well as its varied theoretical contributions across different themes and successful policy application examples, shows that active work done in this city is significant in filling this knowledge gap. Finally, although this review focuses on UHI research in a single city, we hope that our work could also provide useful—and possibly applicable—information to interested stakeholders, such as researchers across (social) scientific disciplines and officials interested in applying research towards sustainable urban climate policy in other cities with different climates.

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REFERENCES

Arnfield, A. J., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.*, **23,** 1–26.

Baker, L. C., A. J. Brazel, N. Selover, C. Martin, N. McIntyre, F. R. Steiner, A. Nelson, and L. Mussacchio, 2002: Urbanization and warming of Phoenix (Arizona, USA): Impacts, feedbacks, and mitigation. *Urban Ecosyst.*, **6**, 183–203.

Balling, R. C., and S. W. Brazel, 1987: Time and space characteristics of the Phoenix urban heat island. *J. Ariz.–Nev. Acad. Sci.*, **21,** 75–81.

——, and R. S. Cerveny, 1987: Long-term associations between wind speeds and the urban heat island of Phoenix, Arizona. *J. Climate Appl. Meteor.*, **26,** 712–716.

——, and S. W. Brazel, 1988: High resolution surface temperature patterns in a complex urban terrain. *Photogramm. Eng. Remote Sens.*, **54,** 1289–1293.

——, and ——, 1989: High-resolution nighttime temperature patterns in Phoenix. *J. Ariz.–Nev. Acad. Sci.*, **23,** 49–53.

——, and P. Gober, 2007: Climate variability and residential water use in the city of Phoenix, Arizona. *J. Appl. Meteor. Climatol.*, **46,** 1130–1137.

——, ——, and N. Jones, 2008: Sensitivity of residential water consumption to variations in climate: An intraurban analysis of Phoenix, Arizona. *Water Resour. Res.*, **44,** W10401, doi:10.1029/2007WR006722.

Brazel, A. J., 1999: Enhancing accountability of the university to serve the public. Preprints, *Eighth Symp. on Education and 11th Conf. on Applied Climatology,* Dallas–Fort Worth, TX, Amer. Meteor. Soc., J1.3.

——, and D. M. Johnson, 1980: Land use effects on temperature and humidity in the Salt River Valley, Arizona. *J. Ariz.–Nev. Acad. Sci.*, **15,** 54–61.

——, and K. Crewe, 2002: Preliminary test of a surface heat island model (SHIM) and implications for a desert urban environment, Phoenix, Arizona. *J. Ariz.–Nev. Acad. Sci.*, **34,** 98–105.

——, N. Selover, R. Vose, and G. Heisler, 2000: Tale of two climates—Baltimore and Phoenix urban LTER sites. *Climate Res.*, **15,** 123–135.

——, H. J. S. Fernando, J. C. R. Hunt, N. Selover, B. C. Hedquist, and E. Pardyjak, 2005: Evening transition observations in Phoenix, Arizona. *J. Appl. Meteor.*, **44,** 99–112.

——, P. Gober, S.-J. Lee, S. Grossman-Clarke, J. Zehnder, B. Hedquist, and E. Comparri, 2007: Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. *Climate Res.*, **33,** 171–182.

Buyantuyev, A., 2005: Land cover classification using Landsat enhanced thematic mapper (ETM) data—Year 2005. [Available online at http://caplter.asu.edu/data/?path5/exist/rest/db/datasets/util/xquery/getDatasetById.xql?_xsl5/db/datasets/util/xslt/datasetHTML.xsl&id5knb-lter-cap.377.1.]

——, and J. Wu, 2010: Urban heat islands and landscape heterogeneity: Linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. *Landscape. Ecol.*, **25,** 17–33.

Cayan, D. R., and A. V. Douglas, 1984: Urban influences on surface temperatures in the southwestern United States during recent decades. *J. Climate Appl. Meteor.*, **23,** 1520–1530.

Changnon, S. A., 1992: Inadvertent weather modification in urban areas: Lessons for global climate change. *Bull. Amer. Meteor. Soc.*, **73,** 619–627.

Cerveny, R. S., S. M. Calderon, M. W. Franjevic, and N. C. Hoffmann, 1992: Development of a real-time interactive storm monitoring program in Phoenix, Arizona. *Bull. Amer. Meteor. Soc.*, **73,** 773–779.

Chow, W. T. L., and M. Roth, 2006: Temporal dynamics of the urban heat island of Singapore. *Int. J. Climatol.*, **26,** 2243–2260.

——, and B. M. Svoma, 2011: Analyses of nocturnal temperature cooling-rate response to historical

local-scale urban land-use/land cover change. *J. Appl. Meteor. Climatol.,* **50,** 1872–1883, doi:10.1175/JAMC-D-10-05014.1.
——, and A. J. Brazel, 2012: Assessing xeriscaping as a sustainable heat island mitigation approach for a desert city. *Build. Environ.,* **47,** 170–181, doi:10.1016/j.buildenv.2011.07.027.
——, R. L. Pope, C. A. Martin, and A. J. Brazel, 2011: Observing and modeling the nocturnal park cool island of an arid city: Horizontal and vertical impacts. *Theor. Appl. Climatol.,* **103,** 197–211, doi:10.1007/s00704-010-0293-8.
——, W.-C. Chuang, and P. Gober, 2012: Vulnerability to extreme heat in metropolitan Phoenix: Spatial, temporal, and demographic dimensions. *Prof. Geogr.,* in press, doi:10.1080/00330124.2011.600225.
City of Mesa, cited 2010: Grass-to-xeriscape landscape rebate program FAQs. [Available online at www.mesaaz.gov/conservation/rebate.aspx.]
City of Phoenix, cited 2008: Sustainable development in a desert climate. Downtown Phoenix Plan, City of Phoenix. [Available online at http://phoenix.gov/urbanformproject/dtplan.html.]
——, cited 2010: Tree and shade master plan. [Available online at http://phoenix.gov/FORESTRY/shade52010.pdf.]
Doran, J. C., C. M. Berkowitz, R. L. Coulter, W. J. Shaw, and C. W. Spicer, 2003: The 2001 Phoenix sunrise experiment: Vertical mixing and chemistry during the morning transition in Phoenix. *Atmos. Environ.,* **37,** 2365–2377.
Elser, M., T. Ganesh, S. Harlan, G. Hupton, D. Medina, and E. Ortiz, cited 2011: Creating a cross-disciplinary unit for middle school children on the urban heat island. [Available online at http://caplter.asu.edu/docs/symposia/symp2011/Elser_etal.pdf.]
Emmanuel, R., and H. J. S. Fernando, 2007: Urban heat islands in humid and arid climates: Role of urban form and thermal properties in Colombo, Sri Lanka, and Phoenix, USA. *Climate Res.,* **34,** 241–251.
Fast, J. D., J. C. Torcolini, and R. Redman, 2005: Pseudovertical temperature profiles and the urban heat island measured by a temperature datalogger network in phoenix, Arizona. *J. Appl. Meteor.,* **44,** 3–13.
Fernando, H. J. S., 2010: Fluid dynamics of urban atmospheres in complex terrain. *Annu. Rev. Fluid Mech.,* **42,** 365–389.
Georgescu, M., G. Miguez-Macho, L. T. Steyaert, and C. P. Weaver, 2008: Sensitivity of summer climate to anthropogenic land-cover change over the greater Phoenix, Arizona, region. *J. Arid Environ.,* **72,** 1358–1373.
——, ——, ——, and ——, 2009a: Climatic effects of 30 years of landscape change over the greater Phoenix, Arizona, region: 1. Surface energy budget changes. *J. Geophys. Res.,* **114,** D05110, doi:10.1029/2008JD010745.
——, ——, ——, and ——, 2009b: Climatic effects of 30 years of landscape change over the greater Phoenix, Arizona, region: 2. Dynamical and thermodynamical response. *J. Geophys. Res.,* **114,** D05111, doi:10.1029/2008JD010762.
——, M. Moustaoui, A. Mahalov, and J. Dudhia, 2011: An alternative explanation of the semiarid urban area "oasis effect". *J. Geophys. Res.,* **116,** D24113, doi:10.1029/2011JD016720.
Gober, P., A. J. Brazel, R. Quay, S. Myint, S. Grossman-Clarke, A. Miller, and S. Rossi, 2010: Using watered landscapes to manipulate urban heat island effects: How much water will it take to cool Phoenix? *J. Amer. Plann. Assoc.,* **76,** 109–121.
Golden, J. S., 2004: The built environment induced urban heat island effect in rapidly urbanizing arid regions—A sustainable urban engineering complexity. *Environ. Sci.,* **1** (4), 321–349.
——, A. J. Brazel, J. Salmond, and D. Laws, 2006: Energy and water sustainability—The role of urban climate change from metropolitan infrastructure. *J. Green Build.,* **1** (3), 124–138.
——, J. Carlson, K. E. Kaloush, and P. Phelan, 2007: A comparative study of the thermal and radiative impacts of photovoltaic canopies on pavement surface temperatures. *Sol. Energy,* **81,** 872–883.
——, D. A. Hartz, A. J. Brazel, G. Luber, and P. Phelan, 2008: A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. *Int. J. Biometeor.,* **52,** 471–480.
Gordon, J. H., 1921: Temperature survey of the Salt River Valley, Arizona. *Mon. Wea. Rev.,* **49,** 271–274.
Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs, 2004: Global change and the ecology of cities. *Urban Ecosyst.,* **319,** 756–760.
Grossman-Clarke, S., J. A. Zehnder, W. L. Stefanov, Y. B. Liu, and M. A. Zoldak, 2005: Urban modifications in a mesoscale meteorological model and the effects on near-surface variables in an arid metropolitan region. *J. Appl. Meteor.,* **44,** 1281–97.
——, Y. Liu, J. A. Zehnder, and J. D. Fast, 2008: Simulations of the urban planetary boundary layer in an arid metropolitan area. *J. Appl. Meteor. Climatol.,* **47,** 752–768.
——, J. A. Zehnder, T. Loridan, and C. S. B. Grimmond, 2010: Contribution of land use changes to near-surface air temperatures during recent summer extreme

heat events in the Phoenix metropolitan area. *J. Appl. Meteor. Climatol.,* **49,** 1649–1664.

Guhathakurta, S., and P. Gober, 2007: The impact of the Phoenix urban heat island on residential water use. *J. Amer. Plann. Assoc.,* **73,** 317–329.

——, and ——, 2010: Residential land use, the urban heat island, and water use in Phoenix: A path analysis. *J. Plann. Educ. Res.,* **30,** 40–51.

Gui, J., P. E. Phelan, K. E. Kaloush, and J. S. Golden, 2007: Impact of pavement thermophysical properties on surface temperatures. *J. Mater. Civil Eng.,* **19,** 683–690.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato, 1999: GISS analysis of surface temperature change. *J. Geophys. Res.,* **104,** 30 997–31 022.

Harlan, S. L., A. J. Brazel, L. Prashad, W. L. Stefanov, and L. Larsen, 2006: Neighborhood microclimates and vulnerability to heat stress. *Soc. Sci. Med.,* **63,** 2847–2863.

Hartz, D. A., A. J. Brazel, and G. M. Heisler, 2006a: A case study in resort climatology of Phoenix, Arizona, USA. *Int. J. Biometeor.,* **51,** 73–83, doi:10.1007/s00484-006-0036-9.

——, L. Prashad, B. C. Hedquist, J. Golden, and A. J. Brazel, 2006b: Linking satellite images and hand-held infrared thermography to observed neighborhood climate conditions. *Remote Sens. Environ.,* **104,** 190–200.

Hawkins, T. W., A. Brazel, W. Stefanov, W. Bigler, and E. M. Saffell, 2004: The role of rural variability in urban heat island determination for Phoenix, Arizona. *J. Appl. Meteor.,* **43,** 476–486.

Hedquist, B. C., and A. J. Brazel, 2006: Urban, residential, and rural climate comparisons from mobile transects and fixed stations: Phoenix, Arizona. *J. Ariz.–Nev. Acad. Sci.,* **38,** 77–87.

Howard, L., 1833: *The Climate of London.* Vol. 1. Harvey and Darton, 348 pp.

Hsu, S.-I., 1984: Variation of an urban heat island in Phoenix. *Prof. Geogr.,* **36,** 196–200.

Jenerette, G. D., S. L. Harlan, A. Brazel, N. Jones, L. Larsen, and W. L. Stefanov, 2007: Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. *Landscape Ecol.,* **22,** 353–365.

——, S. L. Harlan, W. L. Stefanov, and C. A. Martin, 2011: Ecosystem services and urban heat riskscape moderation: water, green spaces, and social inequality in Phoenix, USA. *Ecol. Appl.,* **21,** 2637–2651.

Lee, S.-J., R. C. Balling, and P. Gober, 2008: Bayesian maximum entropy mapping and the soft data problem in urban climate research. *Ann. Assoc. Amer. Geogr.,* **98,** 309–322.

Lee, S.-M., H. J. S. Fernando, and S. Grossman-Clarke, 2007: MM5-SMOKE-CMAQ as a modeling tool for 8-h ozone regulatory enforcement: Application to the state of Arizona. *Environ. Model. Assess.,* **12,** 63–74.

Lee, T. W., and A. Ho, 2010: Scaling of the urban heat island effect based on the energy balance: Nighttime minimum temperature increase vs. urban area length scale. *Climate Res.,* **42,** 209–216.

Martin, C. A., 2008: Landscape sustainability in a Sonoran desert city. *Cities Environ.,* **1** (2), 1–16.

Mills, G., 2006: Progress toward sustainable settlements: A role for urban climatology. *Theor. Appl. Climatol.,* **84,** 69–76.

——, 2007: Cities as agents of global change. *Int. J. Climatol.,* **27,** 1849–1857.

Morehouse, B. J., R. H. Carter, and P. Tschakert, 2002: Sensitivity of urban water resources in Phoenix, Tucson, and Sierra Vista, Arizona, to severe drought. *Climate Res.,* **21,** 283–297.

Oke, T. R., 1976: The distinction between canopy and boundary-layer urban heat islands. *Atmosphere,* **14,** 268–277.

——, 1982: The energetic basis of the urban heat island. *Quart. J. Roy. Meteor. Soc.,* **108,** 1–24.

——, 2006: Towards better scientific communication in urban climate. *Theor. Appl. Climatol.,* **84,** 179–189.

Otanicar, T. P., J. Carlson, J. S. Golden, K. E. Kaloush, and P. E. Phelan, 2010: Impact of the urban heat island on light duty vehicle emissions for the Phoenix, AZ area. *Int. J. Sustain. Transp.,* **4,** 1–13.

Parker, D. E., 2004: Large-scale warming is not urban. *Nature,* **432,** 290.

——, 2006: A demonstration that large-scale warming is not urban. *J. Climate,* **19,** 2882–2895.

Roth, M., 2007: Review of urban climate research in (sub)tropical regions. *Int. J. Climatol.,* **27,** 1859–1873, doi:10.1002/joc.1591.

Ruddell, D., S. L. Harlan, S. Grossman-Clarke, and A. Buyantuyev, 2009: Risk and exposure to extreme heat in microclimates of Phoenix, AZ. *Geospatial Techniques to Urban Hazard and Disaster Analysis*, P. Showalter and Y. Lu, Eds., Springer, 179–202.

Silva, H. R., R. Bhardwaj, P. E. Phelan, J. S. Golden, and S. Grossman-Clarke, 2009: Development of a zero-dimensional mesoscale thermal model for urban climate. *J. Climate Appl. Meteor.,* **48,** 657–668.

——, P. E. Phelan, and J. S. Golden, 2010: Modeling effects of urban heat island mitigation strategies on heat-related morbidity: A case study for Phoenix, Arizona, USA. *Int. J. Biometeor.,* **54,** 13–22.

Stabler, L. B., C. A. Martin, and A. J. Brazel, 2005: Microclimates in a desert city were related to land use and vegetation index. *Urban For. Urban Green.*, **3,** 137–147.

Stewart, I. D., 2011: A systematic review and scientific critique of methodology in modern urban heat island literature. *Int. J. Climatol.*, **31,** 200–217, doi:10.1002/joc.2141.

Stoll, M. J., and A. J. Brazel, 1992: Surface–air temperature relationships in the urban environment. *Phys. Geogr.*, **13,** 160–179.

Sun, C.-Y., A. J. Brazel, W. T. L. Chow, B. C. Hedquist, and L. Prashad, 2009: Desert heat island study in winter by mobile transect and remote sensing techniques. *Theor. Appl. Climatol.*, **98,** 323–335.

Svoma, B. M., and A. J. Brazel, 2010: Urban effects on the diurnal temperature cycle in Phoenix, Arizona. *Climate Res.*, **41,** 21–29.

Wentz, E. A., and P. Gober, 2007: Determinants of small-area water consumption for the city of Phoenix, Arizona. *Water Resour. Manage.*, **21,** 1849–1863.

Wilbanks, T. J., and Coauthors, 2007: Industry, settlement and society. *Climate Change 2007: Impacts, Adaptation and Vulnerability.* M. L. Parry et al., Eds., Cambridge University Press, 357–390.

Yabiku, S. T., D. G. Casagrande, and E. Farley-Metzger, 2008: Preferences for landscape choice in a southwestern desert city. *Environ. Behav.*, **40,** 382–400.